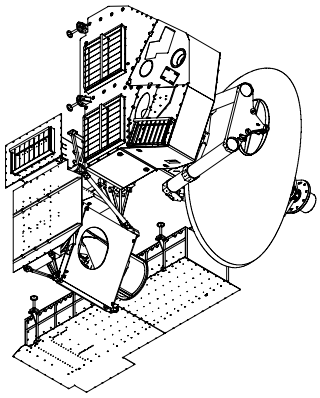
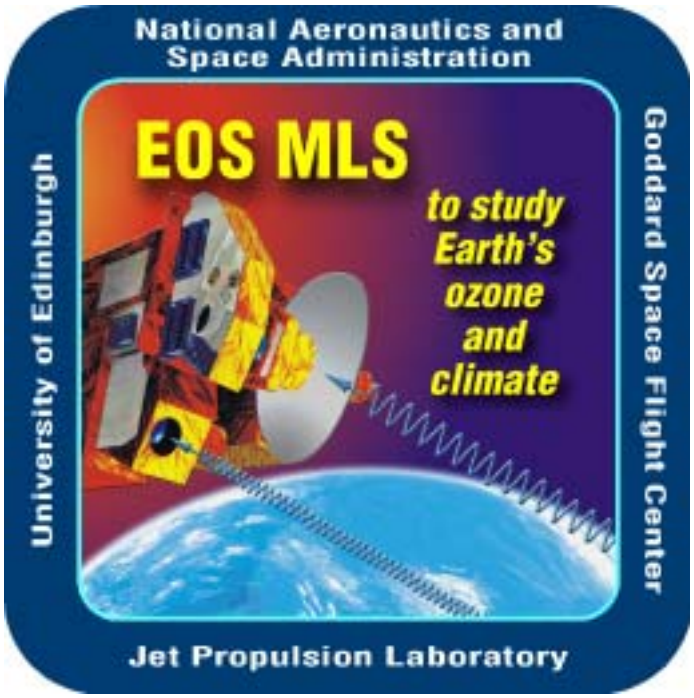
Earth Observing System (EOS)

Microwave Limb Sounder (MLS)

EOS MLS Science Objectives (short version)





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EOS MLS Science Objectives

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table of contents

1 Introduction

EOS MLS is a 'second-generation' MLS experiment, following the 'first-generation' instrument on the Upper Atmosphere Research Satellite (UARS). The major improvements in EOS MLS measurement capability over that of UARS MLS include (1) many more stratospheric species, (2) measurements to lower altitudes, (3) better global coverage with $\pm 82^{o}$ latitude coverage on each orbit, and (4) generally better precision and spatial resolution. The improvement in ozone measurement precision at 100 hPa, for example, is ~20×. MLS measures atmospheric composition, temperature, cloud ice, and pressure from observations of thermal emission at wavelengths between 2.5 mm and 0.12 mm as the instrument field-of-view is scanned down through the atmospheric limb. Unique features of MLS include its ability to measure stratospheric chemical radicals that cannot be measured by other techniques, and to make gas phase measurements in the presence of ice clouds and dense volcanic aerosol.

The MLS geophysical data products, with examples of expected precisions, are given in Table 1-1. MLS looks 'forward' from Aura, and a vertical profile for each geophysical data product is produced every 1.5^{o} along the orbit path. The standard vertical grid is 6 points per decade change in atmospheric pressure (~3 km vertical resolution), with plans to produce a few products (e.g., H_2O in the upper troposphere) on a high resolution vertical grid of 12 points per decade pressure (~1.5 km vertical resolution).

The MLS science objectives are grouped into three categories:

(1) stratospheric ozone,

(2) tropospheric ozone and pollution,

(3) climate variability.

Following sections of this document give objectives in each of these categories. Key questions, as identified by NASA Earth Science Enterprise [2000], provide an overall focus for the objectives and are given (in bold italic font) at the beginning of the section for each category.

Table 1-1. Examples of expected precision (1σ) for MLS data products. Values here are for vertical resolution of 6 points per decade pressure (~3 km). Plots of precision as a function of altitude are given in Filipiak [1999] for all data products, with some values being recent updates. There are trade-offs between precision and resolution. For example, monthly 5° BrO zonal means with vertical resolution of ~2 points per decade pressure (~7 km) will have ~2 pptv precision between 20 and 40 km.

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Data product	**~ vertical range of usefulness**	**Single profile precision**	**monthly 5° zonal mean precision**
temperature	5–80 km	~3 K @ 40 km <2 K @ 5–30 km	better than 0.1 K for ~5-50 km
geopotential ht	5–80 km	<30 m @ 5–30 km	not applicable
BrO	20–40 km	not expected to be useful	12 pptv @ 40 km 8 pptv @ 20 km
CH_3CN	10–50 km	<200 pptv @ 15–25 km ~400 pptv @ 10 km in tropics	<3 pptv @ 15-25 km ~8 pptv @ 10 km tropics
ClO	15–50 km	~0.8 ppbv @ 40 km ~0.3 ppbv @ 20 km	~20 pptv @ 40 km ~7 pptv @ 20 km
CO	10–80 km	<70 ppbv @ 15–25 km ~100 ppbv @ 10 km in tropics	< 1 ppbv @ 15-25 km ~2 ppbv @ 10 km tropics
HCl	15–80 km	~1.5 ppbv @ 50 km <0.4 ppbv @ 15–25 km	~25 pptv @ 50 km <6 pptv @ 15–25 km
HCN	10–50 km	not expected to be useful	~10 pptv @ 30 km
HNO_3	15–40 km	<3 ppbv @ 15–30 km	<0.05 ppbv @ 15–30 km
HOCl	20–40 km	not expected to be useful	~20 pptv @ 25 km
HO_2	25–50 km	not expected to be useful	~150 pptv @ 50 km ~ 20 pptv @ 25 km
H_2O	5–80 km	~1 ppmv @ 50 km ~0.3 ppmv @ 20 km <10% from 5 km to tropopause	~20 ppbv @ 50 km ~ 8 ppbv @ 35 km < 1% from 5 km to trop
N_2O	10–50 km	~60 ppbv @ 40 km ~40 ppbv @ 20 km	~1 ppbv @ 40 km ~0.7 ppbv @ 20 km
OH (upper strat.)	25–80 km	~100 pptv @ 50 km ~5 pptv @ 30 km	~3 pptv @ 50 km ~0.1 pptv @ 30 km
OH (lower strat.)	18–25 km	not expected to be useful	~ 0.2 pptv @ 20 km
O_3	10–80 km	~2% @ 30 km, ~20% @ 50 km <12% within 3 km above trop. <20 ppbv within 3 km below tropopause in tropics	better than 1% throughout the stratosphere <0.3 ppbv within 3 km below tropopause in tropics
SO_2 (volcanic)	15–35 km	<7 ppbv @ 15–35 km	<0.1 ppbv @ 15–35 km
cloud ice (avg over MLS field-of-view)	10–20 km	~1mg/m^3 within ~5 km of tropical trop ~5 mg/m^3 within ~ 2 km of high lat. trop	~0.02mg/m^3 within ~ 5 km of tropical trop ~0.1 mg/m^3 within ~ 2 km of high lat. trop

2 Stratospheric Ozone

How is stratospheric ozone changing, as the abundance of ozone-destroying chemicals decreases and new substitutes increase?

How do stratospheric trace constituents respond to changes in climate and atmospheric composition?

How well can future atmospheric chemical impacts on ozone and climate be predicted?

2.1 Global Stratospheric Ozone and Chemistry

An overarching question is whether global stratospheric ozone will recover as expected in the next few decades, following the international regulations on ozone depleting substances. Stratospheric total chlorine will be near its peak during the Aura mission, and stratospheric total bromine is expected to still be increasing, although more slowly than previously [WMO, 2002]. We thus expect some abatement of ozone depletion during Aura's lifetime and an eventual global recovery, which may not be definitively detectable until later [Reinsel et al., 2002; WMO, 2002]. Climate change could possibly delay ozone recovery – both through stratospheric cooling that can exacerbate some ozone destruction processes, and possibly through changes in transport across the tropical tropopause that could affect the amount of H_2O (and perhaps other substances) in the stratosphere. Projected increases in stratospheric H_2O may delay ozone recovery by 10-30 years [Dvortsov and Solomon, 2001; Shindell, 2001].

2.1.1 Global stratospheric ozone

- **What are the global ozone changes during the Aura mission?** The MLS ozone data will be combined with data from other Aura instruments (and other sources) to collectively produce an accurate record of global ozone changes as part of the longer-term ozone trends record. With significant improvements in precision over UARS, Aura measurements are expected to be especially valuable for quantifying changes in the lower stratosphere.
- **Do we understand global changes in lower stratospheric ozone?** MLS data on N_2O, H_2O, HO_x, BrO, HOCl, and temperature (with other Aura measurements of NO_x) will be used to further constrain and test models of ozone change in this region.
- **Do we understand global changes in upper stratospheric ozone?** Stratospheric ozone declines may reverse first in the upper stratosphere, partly because of the smaller relative effects of dynamics there; climate change also may hasten recovery in this region. MLS profiles of O_3 and ClO will be used as part of the critical data to evaluate this issue.
- **Do we understand variations in source gases that can affect stratospheric ozone?** Large and unexpected changes in stratospheric H_2O and CH_4 occurred in the 1990s [WMO, 1999]. MLS (and other Aura) measurements of H_2O, MLS and HIRDLS measurements of N_2O, and HIRDLS and TES profiles of CH_4, will be used to compare to model expectations and for constraining model predictions of stratospheric ozone change.

2.1.2 Chlorine chemistry

- **Do we understand total stratospheric chlorine variations and trends?** A thorough understanding of changes in the stratospheric chlorine burden is fundamental to determining if ozone is recovering 'as expected'. It is possible that our understanding of

stratospheric chlorine loading is incomplete: Waugh et al. [2001] found an inconsistency in the timing and magnitude of the peak in total chlorine abundance at 55 km deduced from UARS HALOE HCl observations and the amount inferred from surface observations. Upper stratospheric HCl from MLS will be compared to other HCl measurements made during the Aura mission, and to ground-based data for total chlorine.

- **Do we understand stratospheric reactive chlorine variations and trends?** ClO from MLS provides a measure of the rate at which chlorine destroys ozone. As a major improvement over UARS MLS, EOS MLS will measure both ClO and HCl. Changes in the ClO/HCl ratio, measured very accurately by MLS, provide a stringent test of our understanding of stratospheric chlorine chemistry. Variations in total global reactive chlorine can be dominated by factors other than total chlorine (e.g., by unusual changes in CH_4 [Siskind et al., 1998; Froidevaux et al., 2000]). HIRDLS CH_4 data will be essential for understanding observed variations in upper stratospheric ClO.
- **Do we understand middle and upper stratospheric chlorine partitioning?** Aura will provide a suite of global measurements that will be used for a more stringent/extensive test of upper stratospheric chlorine partitioning than previously possible. Relevant measurements include MLS profiles of ClO, HCl, OH and HO_2; HIRDLS profiles of $ClONO_2$ and CH_4; and HIRDLS and MLS profiles of temperature, O_3, N_2O, and H_2O.
- **Do we understand lower stratospheric chlorine partitioning?** Continued global testing of lower stratospheric chlorine partitioning will be performed using MLS measurements of ClO and HCl (and first global measurements of HOCl), along with $ClONO_2$ from HIRDLS, and NO_x from HIRDLS and TES; such testing will be enhanced by observed tracer (N_2O, CH_4) distributions and model comparisons.

2.1.3 Hydrogen chemistry

MLS will provide the first global measurements of OH and HO_2, the key radicals in hydrogen chemistry. This chemistry dominates ozone destruction at ~20-25 km, and above ~45 km, and its understanding is essential for assessing how stratospheric ozone might change in response to climate and composition changes. Our current understanding of hydrogen chemistry in the upper stratosphere is in question due MAHRSI OH observations that do not appear to be consistent with current theory [Conway et al., 2000].

- **Can we understand upper stratospheric and mesospheric hydrogen chemistry?** Simultaneous MLS observations of OH and HO_2 in the upper stratosphere and mesosphere, along with H_2O and O_3, will provide much stronger tests than previously possible of HO_x chemistry and ozone destruction in these regions. This should resolve (or, at least, substantially help resolve) the HO_x dilemma detected in MAHRSI data which show less OH above 50 km than predicted, and more OH below 50 km than predicted.
- **Do we understand hydrogen chemistry couplings in the lower stratosphere?** OH and HO_2 abundances affect the lower stratospheric partitioning among species in the nitrogen, chlorine, and bromine families. The simultaneous MLS observations of OH and HNO_3 and HIRDLS observations of NO_2 (and HNO_3), for example, will allow tests of the expected relationship between these species globally over a wide height range. HO_x also affects active chlorine partitioning as well as the partitioning between active bromine and HBr, and thus provides further constraints on photochemical models of the lower stratosphere.

2.1.4 Bromine chemistry

It is estimated that stratospheric bromine contributes significantly (roughly 30-50%) to the current ozone depletion rate [WMO, 1999]. Bromine abundances in the stratosphere are still increasing, but more slowly than a few years ago [WMO, 2002].

- **Can we understand the global and seasonal variations of stratospheric BrO?** MLS monthly zonal means for BrO will be used to produce the first global climatology of stratospheric BrO profiles and their variations on seasonal and interannual time scales. More localized studies will include polar winter phenomena, comparing the Arctic and Antarctic winter vortices, and the BrO year-to-year variability versus that of ClO. The observed BrO global distribution, seasonal variations, and diurnal variations near the orbit extremes will be compared with predictions from photochemical models.
- **Can we determine and understand total bromine in the upper atmosphere?** The vast majority of bromine above the stratopause is expected to reside in BrO during night. BrO measurements there can determine, or at least help determine, total bromine in the upper atmosphere. This will be investigated with suitably-averaged MLS observations, which may also provide information on stratospheric bromine trends over the Aura mission lifetime.

2.2 Polar Winter Processes

Ozone recovery may be delayed with a colder, more humid stratosphere possibly arising from climate change. The Arctic, in particular, may be at a threshold for more severe O_3 loss in the future. MLS measurements of many species involved in polar processes, as well as O_3 and temperature, will help understand how climate change may affect polar ozone recovery.

2.2.1 Polar winter vortex development and evolution

Development of the vortex in fall and early winter strongly affects conditions later when polar processing occurs. Transport in/through the upper stratosphere is particularly important since air in this region descends to the lower stratosphere in spring [e.g., Plumb et al., 2002].

- **What are the effects of fall vortex development on processing later in winter?** MLS and HIRDLS will provide data on temperature evolution and uncertainties. Global daily fields and tracer correlations from MLS/HIRDLS will be used to study the evolution and origins of air in the polar vortex, and interannual variability in descent and mixing.
- **Where does air in the late winter/spring lower stratospheric vortex originate in fall?** MLS/HIRDLS geopotential height and temperature will be used to calculate winds and descent at higher altitudes than has previously been possible to do routinely with confidence, and H_2O, CH_4, and CO will provide more direct information on descent into the stratospheric vortex, helping to determine origins of air involved in polar processing.

2.2.2 Polar stratospheric clouds

PSCs are known to play pivotal roles in controlling the amount of polar ozone loss, but key aspects of their formation, composition, and sensitivity to climate change are still uncertain.

- **What are the phase and composition of PSC particles, and what are the dominant mechanisms governing their formation?** Many deficiencies in previous studies using satellite data will be ameliorated with simultaneous, colocated HNO_3, H_2O and temperature from MLS/HIRDLS and aerosol from HIRDLS/OMI. Better precision and resolution will

reduce ambiguity in data/model comparisons, and better coverage will allow complete PSC lifecycles and intraseasonal cloud changes to be tracked. Correlating PSC detections based on MLS HNO_3 and HIRDLS aerosol extinction with temperature, tropopause pressure, and column ozone will improve our knowledge of the relative importance of synoptic-scale uplift versus mesoscale temperature fluctuations in promoting PSC formation.

- **Will the spatial extent, duration, or frequency of PSCs increase in the future?** Aura data will help determine whether changes/trends in lower stratospheric temperature and/or H_2O induce significant changes in the prevalence or character of PSCs, especially in the Arctic, where the lower stratosphere now is often only marginally cold enough for PSCs.

2.2.3 Denitrification and dehydration

Ozone loss is influenced by denitrification and dehydration in the polar winter, but these processes and their sensitivity to climate change are still inadequately understood.

- **What are the mechanisms for denitrification, what is its relationship to dehydration, and how sensitive are these processes to changes in temperature or H_2O?** UARS data indicate that denitrification precedes dehydration in the Antarctic [Tabazadeh et al., 2000]. Observation of large HNO_3-containing particles during an unusually cold Arctic winter [Fahey et al., 2001] appears to confirm that these processes are independent, but it remains uncertain whether such large particles form during typical Arctic winters or in the Antarctic. The coverage/quality of temperature, HNO_3, H_2O, and aerosol extinction from MLS and HIRDLS will improve understanding of these processes and their sensitivities.
- **Is widespread severe denitrification necessary for massive ozone loss?** Ongoing processing on sulfate aerosol may be more important than denitrification in maintaining enhanced ClO in spring [e.g., Portmann et al., 1996]. MLS/HIRDLS temperature, aerosol, HNO_3, ClO, HCl, $ClONO_2$, and O_3 data will allow us to clarify the relative importance of denitrification versus chlorine activation on PSCs/sulfate aerosol in facilitating ozone loss.

2.2.4 Chlorine activation, deactivation and the chlorine budget

Understanding chlorine activation, deactivation, and the chlorine budget with its seasonal evolution is crucial for understanding polar ozone loss.

- **Is understanding of chlorine activation, the relative abundances of the main reservoir species, and deactivation in the winter polar lower stratosphere quantitatively correct?** Simultaneous ClO, HCl, and $ClONO_2$ measurements from MLS and HIRDLS will allow chlorine partitioning to be studied in detail. High priority will be given to understanding any discrepancies between the largest values of observed and modeled ClO.
- **Does the chlorine budget balance?** Observations from the 1999/2000 Arctic winter initially indicated a discrepancy in the chlorine budget [WMO, 2002]; reanalysis of the data reduced the discrepancy but did not eliminate the possibility of 'missing' chlorine species. MLS/HIRDLS ClO, HCl, $ClONO_2$, and CFC11 and CFC12 will help resolve this issue.
- **Are there unknown photolytic processes that enhance chlorine destruction of O_3?** Models substantially underestimate O_3 loss during cold Arctic winters, and recent analyses [Rex et al., 2003] implicate an unknown process involving photolysis at high solar zenith angles. Comparing MLS ClO and O_3 with model results will help identify the mechanism.

2.2.5 Chemical ozone loss in polar winter

Different methods and datasets give qualitatively similar results in current Arctic ozone loss studies, but detailed quantitative agreement is lacking and hampered by limited data and large uncertainties in loss estimates. Outstanding issues in the Antarctic include predicting the onset of ozone loss, quantifying midwinter loss, and understanding loss in the subvortex.

- **How well can we quantify ozone loss throughout the winter, in both the Arctic and Antarctic?** Four general methods have been used to estimate ozone loss [e.g., Harris et al., 2002]: 'Match' techniques, calculations of vortex-average descent and O_3 changes, comparisons of observed O_3 with passive O_3 in transport models, and evolution of O_3/tracer correlations. Using these methods with MLS data will greatly improve estimates of O_3 loss and quantification of their uncertainties. Aura tracer data will be used to assess applicability and limitations of the tracer correlation method applied to satellite measurements.
- **What are the relative contributions of polar dynamical and chemical processes to long-term ozone changes?** Improved column ozone loss estimates from Aura data will be used with dynamical models to improve our understanding of the relative importance of dynamical and chemical processes in Arctic ozone variability.

2.3 Dynamics and Transport

Understanding stratospheric dynamics and transport is essential for understanding stratospheric O_3 and its variations. Unique MLS contributions in this area include routine measurements every 1.5^o along the orbit track, and measurements in the presence of ice clouds and aerosol that can degrade infrared, visible and ultraviolet measurements.

2.3.1 Dynamical effects on ozone trends

Downward trends in midlatitude ozone [e.g., Staehelin et al., 2002] arise from a combination of chemical and dynamical processes. Both day-to-day [e.g., Hood et al., 2001] and interannual [e.g., Appenzeller et al., 2000] O_3 variability are strongly related to dynamical processes. Variability and trends in wave propagation, Rossby wave-breaking, and tropopause characteristics have direct effects on column ozone. Summertime ozone variability has been related to Rossby-wave propagation and to the dynamics of the vortex breakup. Dynamical and transport processes are intimately involved in extra-tropical stratosphere-troposphere exchange.

- **What are the roles of dynamical and transport processes in day-to-day, seasonal and interannual ozone variability?** Daily 3D O_3 fields from MLS/HIRDLS will be used to quantify the roles of dynamical processes in O_3 variability. Relationships between lower stratospheric temperatures, tropopause heights, column O_3, 3D O_3 structure and wave fluxes (all of which can be derived from MLS and/or HIRDLS data) will be studied. MLS/HIRDLS O_3 and H_2O in the upper troposphere and lower stratosphere (UT/LS) will be used to relate trends/variability in extratropical stratosphere-troposphere exchange to dynamical processes.
- **What are the processes governing relationships between changes in stratospheric ozone, tropopause height, and UT/LS dynamical variations?** Tropopause height, temperature and other dynamical properties derived from MLS and HIRDLS temperature and geopotential height will be correlated with observed column O_3 to elucidate relationships between changes in the two, and analyzed with ozone profiles to understand the mechanisms behind these relationships.

2.3.2 Effects of polar processes on midlatitude ozone

Polar vortex processes can affect midlatitude ozone through export of PSC-activated air with subsequent in-situ midlatitude ozone loss and through export of ozone-depleted air. However, observations to date have been inadequate for quantifying these two effects. Aura data will allow a more detailed quantitative study of them.

- **How well can we quantify the export of vortex-processed air to midlatitudes?** The evolution of 3D trace gas fields will be examined to identify and quantify export of vortex-processed air. Vortex and extravortex tracer correlations differ strongly in late winter and spring, due to effects of descent/mixing and chemical/microphysical processes; such correlations will be used to identify and study air transported out of the vortex. Air parcel history calculations will identify the origins of air escaping from the vortex. The 1.5^{o} degree along-track spacing of MLS measurements is particularly useful for identifying vortex filaments, and the 1 km vertical resolution of HIRDLS is particularly suited to detecting laminae that arise from such filaments.
- **How well can we model the effects of vortex-exported air on midlatitude ozone?** 3D trace gas fields from Aura will be used to initialize chemical transport models (CTMs) for detailed modeling studies of transport of air from the polar vortex and for comparison with model results. MLS and HIRDLS observations will be used to identify the composition of air exported from the vortex for modeling in situ loss in midlatitudes.

2.3.3 Tropical transport and its effect on stratospheric ozone

Understanding the tropical tropopause region is crucial to predicting trends in stratospheric H_2O and hence the recovery of ozone, yet our current understanding is so poor that we cannot even explain the sign of the observed H_2O trend. Seasonality and interannual variability in the tropical tropopause temperature is consistent with control by the stratospheric residual circulation, which is driven by extratropical wave activity. The relative roles of stratospheric residual circulation and convectively-driven disturbances are now a topic of scientific debate.

- **Can we obtain better estimates of vertical velocity and related parameters, and thus a better understanding of the stratospheric "tape recorder"?** Rising tropical air remains remarkably little changed by other stratospheric air or by vertical mixing – the seasonal cycle of stratospheric H_2O is preserved for ~1.5 years as the air rises. Several attempts have been made to quantify horizontal dilution and vertical diffusion rates. The multi-year datasets of H_2O and CH_4 from Aura will permit us to better address this issue, and look for interdecadal variability resulting from anthropogenic changes in atmospheric composition.
- **What are the effects of the seasonal cycle and quasi-biennial oscillation (QBO) on stratospheric ozone?** The QBO influences the distribution of stratospheric ozone in several ways. The secondary residual circulation induced by it results in temperature fluctuations, which affect temperature-dependent photochemistry of O_3 and the entry value of H_2O that can affect O_3 chemistry. The QBO influences wave propagation into the tropics that shapes the distribution of trace constituents. Analyses of Aura O_3 and H_2O measurements over several annual and QBO cycles will extend our understanding of how the QBO and annual cycle interact to influence stratospheric ozone and tracer distributions.

2.3.4 Gravity waves and their effect on stratospheric circulation and ozone

Gravity waves (GWs) play important roles in determining atmospheric circulation and thermal structure. Comprehensive atmospheric models used in ozone loss studies rely on GW parameterizations to produce realistic stratospheric polar vortex and temperature distributions, but current parameterizations are crude and quite arbitrary with many *ad hoc* settings.

- **What is the global distribution of gravity waves, and their propagation and source properties?** GWs are generated from flow over mountains, deep convection, etc., but their sources and distributions are highly uncertain. MLS will measure GWs with >~5 km vertical and > ~100 km horizontal wavelengths, and HIRDLS with >~1 km vertical and >~300 km horizontal wavelengths; these will provide important constraints to GW theories and model parameters. Comparative studies of observations (Aura, GPS, ground-based) and mechanistic model simulations should offer unprecedented insight into GW processes.
- **To what extent do gravity waves contribute to PSC formation?** The uncertainty of GWs' role in PSC formation hinders the reliable prediction of future ozone loss in the polar region. GW-related PSC formation will be investigated in conjunction with HIRDLS, TES and OMI PSC measurements, as MLS GW observations can be made simultaneously at these PSC locations but are not contaminated by the clouds.

2.4 Dehydration of the Stratosphere

How and why stratospheric humidity has been increasing for the last few decades [e.g., Rosenlof et al., 2001] has important implications for stratospheric O_3 [e.g., Dvortsov and Solomon, 2001] and radiative forcing of climate [e.g., Smith et al., 2001]. Knowledge of the mechanisms regulating stratospheric humidity is required to adequately understand processes, including potentially important feedbacks, affecting both O_3 and climate. Dehydration mechanisms in the Tropical Tropopause Layer (TTL) clearly remove most of the tropospheric H_2O, and two theories for this mechanism have emerged. "Convective dehydration" [e.g., Sherwood and Dessler, 2001] posits that air emerges from convection fully dehydrated (on average) to stratospheric values. "Gradual dehydration" [e.g., Holton and Gettelman, 2001] posits that air is dehydrated after detrainment from convection by repeated exposures to episodic cold events as it slowly ascends into the stratosphere.

- **Does convection hydrate or dehydrate the TTL?** MLS measurements of the 3D structures of H_2O and other trace gases around the tropical tropopause will help determine the extent to which convection hydrates or dehydrates the TTL. Because low O_3 (high CO) indicates air that has been recently transported from the planetary boundary layer, coincidence between regions of low H_2O and low O_3 (high CO) indicates convective dehydration. Lack of such a coincidence indicates gradual dehydration.
- **What role does the Asian monsoon play in regulating stratospheric humidity?** The Asian monsoon has come under increasing scrutiny as a major player in the water budget near the tropopause. Moistening of the TTL and midlatitude lowermost stratosphere appears clearly in observations [e.g., Randel et al., 2000], but it is unclear how the monsoon affects air entering the stratosphere at potential temperatures above 380 K. MLS (and HIRDLS) fields of H_2O, O_3, and other tracers, in combination with transport model studies, will be used to trace the motion of H_2O for determining the Asian monsoon's role.
- **What is the role of thin cirrus in the TTL?** The role of thin cirrus in the H_2O budget of the TTL is uncertain. The combination of MLS (and HIRDLS) H_2O and temperature

measurements and HIRDLS and Aqua MODIS measurements of thin cirrus, will provide insight into the role of these clouds. We will examine from a broad viewpoint whether thin cirrus formation is slaved to local temperature or if other factors (e.g., air mass history) are important. The humidity field evolution will be correlated with cirrus occurrence and environmental conditions to yield critical constraints on the dehydration role of cirrus.

2.5 Volcanic Effects on Stratospheric Ozone

Stratospheric aerosol variability over the past 25 years has been dominated by the effects of episodic volcanic eruptions [WMO, 2002], and 30% of the last 150 years have been characterized by volcanic clouds as optically thick as Arctic PSCs [Tabazadeh et al., 2002]. An explosive, sulfur-rich volcanic eruption within the next few decades – when stratospheric chlorine loading is still high – could have profound consequences. If a major volcano erupts during the Aura mission, MLS objectives will include addressing the following key questions.

- **How does volcanically-enhanced sulfate aerosol perturb stratospheric nitrogen and chlorine concentrations?** Following volcanic eruptions, the SO_2 injected into the stratosphere is rapidly converted into sulfate aerosol, greatly extending the latitudinal, altitudinal, and temporal ranges over which heterogeneous processes alter nitrogen and chlorine partitioning [e.g., Solomon, 1999]. These perturbations will be investigated with Aura measurements of HNO_3, N_2O_5, NO_2, ClO, HCl, $ClONO_2$, and column OClO.
- **How does volcanically-enhanced sulfate aerosol affect PSC formation/denitrification?** Models indicate that under volcanic conditions the sulfate-rich composition of ternary solutions hampers formation of solid PSCs [Tabazadeh et al., 2002], limiting the effectiveness of PSC particles in causing denitrification. Aura measurements of temperature, H_2O, HNO_3, and aerosol extinction will be used to assess differences in PSC character and denitrification between volcanically perturbed and quiescent periods.
- **How do volcanoes affect stratospheric ozone?** Dynamical effects associated with volcanic aerosol can reduce column O_3 in the tropics, while perturbations to nitrogen and chlorine partitioning can cause increased chemical O_3 depletion at mid/high latitudes [e.g., Solomon, 1999]. With Aura, we will be able to quantify these volcanically-induced changes in ozone.
- **Will climate change make the stratosphere more vulnerable to ozone depletion after a volcanic eruption?** Stratospheric cooling and H_2O increases will likely have a greater effect on stratospheric ozone under conditions of volcanically-enhanced aerosol. A major volcanic eruption during the Aura timeframe, when stratospheric chlorine loading will be higher, could thus have an even greater impact on ozone than the 1991 Mt. Pinatubo eruption.

3 Tropospheric Ozone and Pollution

What are the effects of regional pollution on the global atmosphere, and the effects of global chemical and climate changes on regional air quality?

Tropospheric ozone, an important pollutant and contributor to urban smog, has increased since pre-industrial times. In addition to its more direct effects on air quality, tropospheric ozone is a source for OH which regulates air's ability to cleanse itself of many polluting and greenhouse gases. Aura is a major step forward in tropospheric observations, with TES global measurements of many species. MLS complements TES in the upper troposphere, with some science objectives itemized below, and MLS measurements can be made in the presence of (and through) cirrus that degrade TES data. MLS single profile measurement precision will generally

be sufficient for H_2O, temperature and O_3 in the upper troposphere. Biweekly or monthly maps will generally be needed for CO, CH_3CN and HCN – but single profiles will be useful when abundances are substantially enhanced (e.g., by biomass burning). Correlative aircraft measurements, valuable for many MLS (and Aura) science objectives, are especially important for several aspects of the MLS tropospheric studies (e.g., validation, better precision and spatial resolution, complementary data, and extending the analysis range into the lower troposphere).

- **What is the quantitative connection between global upper tropospheric pollution and biomass burning/surface pollution?** Biomass burning is known to be a significant contributor to tropospheric column O_3 enhancements over the South Atlantic [e.g., Fishman et al., 1990] and to CO enhancements in the Pacific upper troposphere [Matsueda et al., 1999]. Direct linkage between biomass burning and upper tropospheric pollutant enhancement events has been established [Andreae et al., 2001]. A localized enhancement in lower stratospheric CH_3CN detected and tracked by UARS MLS has been traced to an intense thunderstorm's injection of forest fire pollution into the stratosphere [Livesey et al., 2003]. An EOS MLS objective is to better quantify such events and their global effect. Correlations of MLS O_3, CO, CH_3CN and HCN will provide data on the sources of O_3 and CO enhancements. Such studies will be optimized through the use of several Aura products (e.g., NO_2 column and aerosol from OMI; O_3, CO and CH_4 from TES).
- **Can we determine and understand global tropospheric column ozone variations?** Stratospheric column ozone from MLS (and HIRDLS) will be used in combination with OMI total ozone column to produce daily maps of tropospheric ozone residual (TOR) column. Improved tropospheric column ozone quality is expected from the OMI-MLS (and OMI-HIRDLS) TOR products; these will supplement tropospheric ozone columns measured directly by TES (which typically will have a 50% duty cycle). These data will be compared to 3D models (as constraints for improving tropospheric models).
- **What is the global upper tropospheric ozone distribution/budget?** Upper tropospheric ozone measurements from MLS, TES and HIRDLS will be used to produce a more detailed global description of the upper tropospheric ozone field, and its budget/variations, than has previously been possible. Aura global tropospheric data should dramatically increase constraints on tropospheric models. Stratosphere-troposphere exchange is a significant source for ozone in the upper troposphere [Lelieveld and Dentener, 2000], and improvements in estimates of ozone flux from stratosphere (and model parameterizations of it) should be possible withAura data. MLS measurements in the presence of cirrus and HIRDLS high-resolution measurements are especially important in this regard.
- **Can we determine and understand interannual and longer-term upper troposphere changes?** While seasonal variations of upper tropospheric O_3 seem to be fairly well captured by models [e.g., Law et al., 2000], better characterization and understanding of longer-term changes are needed. Pollution transport is episodic [e.g., Yienger et al., 2000] and requires understanding on a global, interannual, and long-term basis. This includes issues such as variability related to El Niño and expected increases in pollution from Asia. Constraints from Aura data should improve our ability to determine tropospheric changes.

4 Climate Variability

What trends in atmospheric constituents and solar radiation are driving global climate?

How well can transient climate variations be understood and predicted?

How well can long-term climate trends be assessed or predicted?

How well can future atmospheric chemical impacts on ozone and climate be predicted?

4.1 Climate Processes Involving Upper Tropospheric H_2O

A key uncertainty in predicting future climate changes is the response of tropospheric H_2O to changes in the greenhouse gas concentration. The small amounts of H_2O in the upper troposphere (UT) have a particularly strong infrared radiative effect, due to the low temperatures there, and exert enormous leverage on Earth's radiative balance. Increases in upper tropospheric H_2O within global climate models result in much greater radiative effects at the surface than are caused solely by the build-up of CO_2 and other greenhouse gases [e.g., Shine and Sinha, 1991]. Of particular importance is the moisture in the dry subtropical regions, which has a large cooling effect on the whole tropics [Spencer and Braswell, 1997]. There is large uncertainty on the actual abundance of H_2O in this region, due to lack of data.

Understanding the mechanisms that control humidity of the tropical troposphere is key to determining the nature of its feedback on climate, and is thus essential for improving climate change predictions. The subtropics are not as dry as the simple picture of outflow and subsidence from equatorial convective regions would imply – hence there must be additional moisture sources that hydrate the regions of the tropics characterized by descent. There are three hypotheses for the sources of this moisture: (1) evaporation of precipitation, (2) evaporation of detrained cloud particles, and (3) lateral transport. The relative contribution of these sources to subtropical moisture has major implications on how subtropical humidity will change in response to climate change and, hence, major implications for the water vapor feedback on climate [e.g., Pierrehumbert, 2000]. Improving our understanding of these sources is crucial for climate models to accurately simulate tropospheric water vapor and its feedbacks.

- **What is the distribution of upper tropospheric water vapor, and how does it vary on seasonal and interannual time scales?** EOS MLS will provide accurate H_2O measurements in the tropical and subtropical upper troposphere, even in the presence of cirrus where observations by other techniques can be flawed. These measurements will enable the distribution and temporal variation of upper tropospheric humidity (UTH) to be accurately determined. The better accuracy and precision, and spatial and temporal coverage, of EOS MLS – and its extension of the UARS data set over a longer time period – will further improve our knowledge of UTH.
- **What are the processes controlling upper tropospheric humidity?** Joint analysis of the MLS UTH measurements and the location and strength of deep convection and the circulation (e.g., from outgoing longwave radiation measurements) will improve understanding of how deep convection affects upper tropospheric humidity. Aura measurements of tracers will provide information on the origin of the air mass, and may place further constraints on the hydration paths for upper tropospheric water. MLS measurements of cirrus ice content will provide important data on the supply of water to the upper troposphere – helping, for example, determine what fraction of water in a

convective air parcel remains in condensed form that can rapidly fall out. Variation in the observed UTH over seasonal through interannual time scales will provide insight into how different forcings, such as El Nino, may affect climate variability. Observed UTH will help determine how well models can reproduce the observed distribution, and thus will test our understanding of processes controlling upper tropospheric H_2O (e.g., comparisons with models that determine the humidity by tracing air parcels to the temperature of last saturation will test the "lateral transport" hypothesis).

4.2 Radiational Effects of Stratospheric O_3 and H_2O on Climate

- **How might changes in stratospheric O_3 and H_2O affect stratospheric climate?** In addition to effects on stratospheric temperature, O_3 and H_2O changes are expected to affect stratospheric circulation in ways difficult to predict. As well as direct effects (e.g., influence of the change in heating/cooling on the vertical static stability and meridional temperature gradients), there is a feedback via geostrophic balance on the magnitude of zonal mean winds. This impinges on the propagation of tropospheric planetary waves into the stratosphere and the rate at which they are damped and dissipated, affecting strength of the diabatic circulation. Understanding the interaction of these processes entails calculation of 3D heating and cooling fields, which requires accurate H_2O and O_3 throughout the stratosphere. There is wide disparity in the calculated effects of changes in O_3 and H_2O on stratospheric temperature. A major source of the disparity is uncertainty in the vertical distribution of stratospheric H_2O trends [Shine et al., 2003]. MLS and HIRDLS will accurately measure O_3 and H_2O in the region of most uncertainty, allowing effects of future changes to be more accurately predicted.
- **How might changes in stratospheric O_3 and H_2O affect forcing of surface temperature?** Greenhouse forcing of surface temperature is significantly influenced by radiative effects of O_3 and H_2O in the lower stratosphere and around the tropopause [IPCC, 2001]. A given *fractional* change in O_3 has the largest effect on surface forcing when it occurs in the upper troposphere and lower stratosphere [Forster and Shine, 1997], but O_3 changes in these regions are poorly characterized. As a consequence, understanding of greenhouse forcing by stratospheric O_3 changes is now classified as only 'medium' [IPCC 2001]. Radiative forcing by stratospheric H_2O trends is expected to be comparable (and opposite in sign) to that due to O_3 depletion [Forster and Shine, 2002]. The important contribution to surface forcing by H_2O in the near-tropopause region, where its distribution and variation are poorly characterized, has been highlighted in a number of studies. Aura measurements of O_3 and H_2O will reduce uncertainties in their contributions to future changes.

4.3 Climatic Effects of Volcanic SO_2

- **How does volcanic SO_2 injected into the stratosphere affect climate?** Volcanoes can inject large amounts of SO_2 into the stratosphere. This is converted by reaction with OH into sulfuric acid, which condenses into aerosols whose scattering of shortwave solar radiation leads to surface cooling, and whose absorption of upwelling longwave radiation leads to lower stratospheric heating. MLS measurements of SO_2 and OH vertical profiles will allow more stringent tests than previously possible for models of stratospheric aerosol formation from volcanic SO_2. Its measurements of temperature, tracers, and geopotential height – all of which can be made in the presence of dense aerosol – will provide unique information on the short term response of stratospheric temperature and circulation to aerosol increases.

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